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Complementary Beam-forming

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Outline

- Motivation
- Smart Antenna Enhancements to IEEE 802.11 Systems
- Problems with Conventional Beam-Forming in CSMA Systems
- Complementary Beam-Forming (CBF)
- Analysis of CBF for Silent and Intended Users
- Examples

Motivation

- Current IEEE 802.11 wireless LANs support a maximum throughput of 54 Mbps.
- Such a throughput is only achievable in a radius of 4 meters (AT&T-Harvard Measurements and Models)
- At present, a "Wi-Fi revolution" is taking place.
- It is anticipated that the widespread deployment of Wi-Fi will change the entire wireless landscape in few years.

Motivation

- There will be an abundance of data hungry users in *hot spots*.
- WLAN providers will have to seek devices with increased throughputs and ranges
- This has forced an enormous body of industrial and research activities.

Smart Antennas Solution

- An enhancement that seems to provide an appealing solution is the use of antenna arrays at access points (AP) in conjunction with beam-forming.
- Such a solution is transparent to receivers and does not force any changes to current standards and receivers.
- In spite of these benefits, design of beam-forming enhancement to WLANs is not as trivial as said above as the combination of beam-forming and the CSMA protocol produces a host of new problems.

Beam-Forming and CSMA

- Consider a scenario where there are $m = 2$ transmit antennas and $k = 1$ intended users.
- Let the channel matrix to the desired user be given by (α, β).
- A conventional beam-former then induces weigths

$$w_1 = \frac{\bar{\alpha}}{|\alpha|^2 + |\beta|^2}$$
$$w_2 = \frac{\bar{\beta}}{|\alpha|^2 + |\beta|^2}$$

  at the transmitter.
- If c_1 is the intended transmit signal at time 1 for user 1, then $w_1 c_1$ and $w_2 c_1$ are transmitted signals from antennas 1 and 2 respectively.

Beam-Forming and CSMA

- The intended user receives the signal

$$r_1 = w_1 c_1 + w_2 c_1 + n_1 = \sqrt{|\alpha|^2 + |\beta|^2} c_1 + n_1,$$

  where n_1 is the noise.

- The signal to noise power ratio of the desired user improves by a factor of $10 \log_{10}(\sqrt{|\alpha|^2 + |\beta|^2})$ dB.
- This is not a free gain!

The Hidden Beam Problem

- Let an unintended user have channel matrix $(-\bar{\beta}, \bar{\alpha})$.
- Then the signal at this unintended user is given by

$$y_1 = -\bar{\beta} w_1 c_1 + \bar{\alpha} w_2 c_1 + \eta_1 = \eta_1,$$

  where η_1 is the noise vector and the unintended user receives no signal.
- $\rightarrow$ With conventional beam-forming some users may have low signal components.
- This can cause a problem in a CSMA system.

The Hidden Beam Problem

- In CSMA, all users and the access point share the same channel for both up-link and down-link transmissions.
- Each user senses the channel and only transmits packets if it determines that the channel is not busy.
- A user with no adequate signal component may wrongly determine that the channel is idle (when busy) and start transmitting packets.
- This may cause unnecessary transmissions, subsequent back-offs, increased network latency and interference.
- Furthermore, the aforementioned undesired packet transmission has an energy penalty which adversely effects the battery life of the remote devices.
- This is called the *Hidden Beam Problem.*

The Hidden Beam Problem

- In lightly loaded systems (for instance with only one user), the hidden beam problem is not important.
- This "*Hidden Beam Problem*" is further exuberated if the system is more heavily loaded.
- This will be most likely the case both in hot spots or if the system range is increased.

Complementary Beam-Forming: Idea

- The main intuition behind complementary beam-forming is: Detection of busy period is easier than decoding of transmitted packet.
- This is built in the IEEE 802.11 WLAN standards.
- Each device listens to the channel during some time window and compares the energy collected in this window to a CCA (Clear Channel Assessment) threshold.
- Detect activity: if the collected energy $\geq$ the CCA threshold.
- Thus we will seek to construct a beam pattern which directs most of the transmitted power to the intended recipients while directing a small fraction of the total power to unintended users.

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- This is built in the IEEE 802.11 WLAN standards.
- Each device listens to the channel during some time window and compares the energy collected in this window to a CCA (Clear Channel Assessment) threshold.
- Detect activity: if the collected energy $\geq$ the CCA threshold.
- Our solution (CBF): Construct a beam pattern which directs most of the transmitted power to the intended recipients while directing a small fraction of the total power to unintended users.

Notation

- For any vector X, we let X^T and X^H respectively denote the transpose and Hermitian of X.
- For any matrix D, we let W_D denote the vector space spanned by the columns of D.
- Let the channel from transmit antenna l to the intended user j be given by $\alpha_{l,j}$.
- Let A_j denote the column vector $(\alpha_{1,j}, \alpha_{2,j}, \cdots, \alpha_{m,j})^T$. We refer to the vector A_j as the *spatial signature of user* j.
- Let A denote the matrix whose j-th column is A_j.
- Let $R^t = (r_1^t, r_2^t, \cdots, r_k^t)$ and $X^t = (x_1^t, x_2^t, \cdots, x_m^t)$ respectively denote the vector of received signals at intended users $j = 1, 2, \cdots, k$ and the vector of signals transmitted from

antennas $1, 2, \cdots, m$ at time t.

- Let $C^t = (c_1^t, c_2^t, \cdots, c_k^t)$, where c_j^t is the signal intended to the $j = 1, 2, \cdots, k$ desired user at time t.
- For any square matrix A, let $Tr(A)$ denotes the trace (sum of diagonal elements of A).
- Let $N^t = (n_1^t, n_2^t, \cdots, n_m^t)$ be the noise vector components at time t at the intended users.

Beam-Forming Matrix

- Then

$$R^t = X^t A + N^t, \tag{1}$$

- Noise components are assumed to be i.i.d. Gaussian.
- *No assumptions* on the statistics of the matrix A.
- c_j^t, $j = 1, 2, \cdots, k$, $t = 1, 2, \cdots, L$ are elements of a signal constellation with average signal $E[c_j^t] = 0$.
- The elements of the signal constellation are normalized so that their average power is $E[|c_j^t|^2] = 1$.
- In general $X^t = C^t \mathcal{B}$ where $\mathcal{B}$ is referred to as the *beam-forming matrix.*

ZF and Max-SINR Beam-Forming

- Then for a zero-forcing beam-former

$$\mathcal{B} = \frac{(A^H A)^{-1} A^H}{\sqrt{Tr((A^H A)^{-1})}}$$

  and

- We present our technique for the zero-forcing beam-former here. Generalization to the maximum SINR case is obvious.
- We assume that the spatial signature matrix A is constant during the transmission of a packet.

Complementary Beam-Forming

- let W_A denote the vector space spanned by the columns of A.
- The subspace W_A is a k-dimensional subspace of the complex m-dimensional complex space
- Let $W_A^\perp$ be the orthogonal complement of W_A. $W_A^\perp$ has dimension $m-k$.
- Let $U_0, U_1, \cdots, U_{m-k-1}$ form an orthonormal basis for $W_A^\perp$. (In other words, $U_0, U_1, \cdots, U_{m-k-1}$ are mutually orthogonal m-dimensional column vectors of length one in $W_A^\perp$).
- Clearly, $U_j^H A_i = 0$ for $0 \leq j \leq m-k-1$ and $1 \leq i \leq k$.

Complementary Beam-Forming

- The transmitter constructs matrices $Z_1, Z_2, \cdots, Z_L$, where L is the the length of down-link transmission period, such that:
  - **A:** For all $1 \leq i \leq L$, the matrix Z_i is a $k \times m$ matrix whose rows are in the set $\{0, \pm U_0^H, \pm U_1^H, \cdots, \pm U_{m-k-1}^H\}$,
  - **B:** If L is even, then $Z_2 = -Z_1$, $Z_4 = -Z_3, \cdots, Z_L = -Z_{L-1}$,
  - **C:** If L is odd, then $Z_2 = -Z_1$, $Z_4 = -Z_3, \cdots, Z_{L-1} = -Z_{L-2}$, $Z_L = 0$, and
  - **D:** Each element

$$+U_0^H, -U_0^H, +U_1^H, -U_1^H, \cdots, +U_{m-k-1}^H, -U_{m-k-1}^H$$

appears p times in the the list of Lk rows of $Z_1, Z_2, \cdots, Z_L$ for some positive integer p.

Complementary Beam-Forming

- Once $Z_1, Z_2, \cdots, Z_L$ are constructed, at each time t, the transmitter chooses the beam-forming matrix

$$S^t = [((A^H A)^{-1} A^H / \sqrt{Tr((A^H A)^{-1})} + \frac{1}{\sqrt{k}} \epsilon Z_t], \tag{2}$$

  where $\epsilon \geq 0$ is a fixed positive number.

- The choice of $\epsilon \geq 0$ governs the trade-off between the power pointed to the intended users and that pointed to unintended users.

- For $\epsilon = 0$, we recover the conventional beam-forming $\rightarrow$ Complementary beam-forming generalizes and includes conventional beam-forming as a special case.

Analysis of CBF

Intended Users

- **Theorem:** The intended users in complementary beam-forming when compared to the conventional method suffer a loss of at most $10\log_{10}(1+|\epsilon|^2)$.

Analysis of CBF

Silent Users

- **Theorem:** Let $\lambda_{\min}(A^H A)$ and $\lambda_{\max}(A^H A)$ respectively denote the minimum and maximum eigenvalues of $A^H A$. Then provided that

$$|\epsilon|^2 \leq \frac{(m-k)}{k} \frac{\lambda_{\min}(A^H A)}{\lambda_{\max}(A^H A)}, \tag{3}$$

$$p \geq \frac{m}{k} - 0.5, \tag{4}$$

complementary beam-forming guarantees a fraction $|\epsilon|^2 \frac{\sum_{j=1}^{m} |b_j|^2}{m}$ of the transmitted power to an unintended receiver whose spatial signature is $B = (b_1, b_2, \cdots, b_m)$.

Comment

- The condition $p \geq \frac{m}{k} - 0.5$ means that the transmitted packets must not be too short.
- The condition

$$|\epsilon|^2 \leq \frac{(m-k)}{k} \frac{\lambda_{\min}(A^H A)}{\lambda_{\max}(A^H A)},$$

$$p \geq \frac{m}{k} - 0.5,$$

  is a natural one, because when $\lambda_{\min}(A^H A)/\lambda_{\max}(A^H A)$ is small. Then the matrix $A^H A$ is close to being singular. This means that even the intended users, do not receive significant signal powers

- In loaded systems, schedulers take care of this ssue and choose the users for which the above ratio is larger than a threshold.

Example

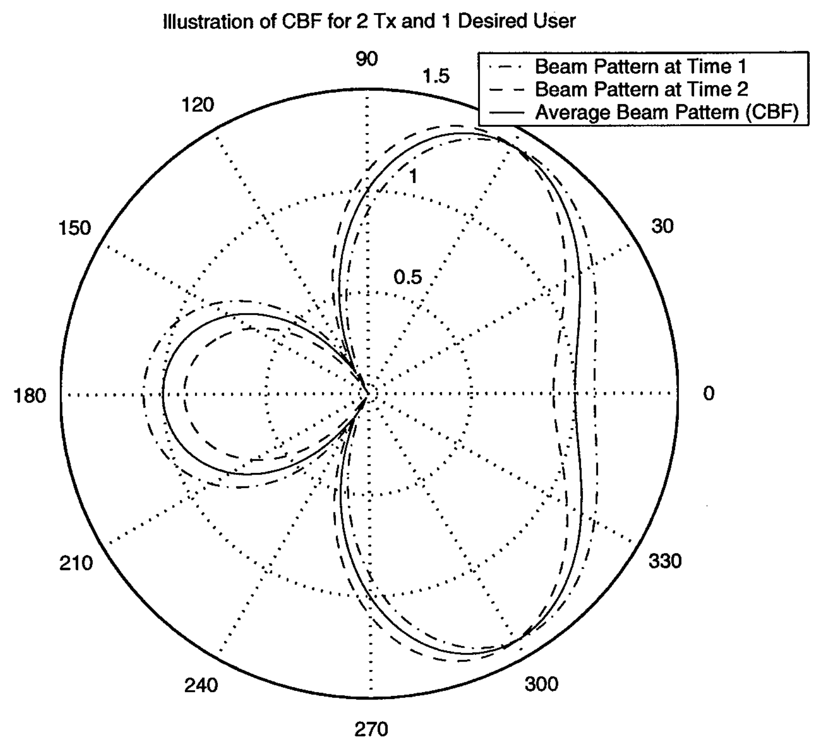
- We consider the case when there are $m = 2$ transmit antennas and $k = 1$ intended receivers. Let $\epsilon = 0.1$.
- The above Theorems say that power of 20 dB below the transmitted power is guaranteed to silent users. The loss to the intended user is at most 0.044 dB.
- The beam-forming matrices S_1 and S_2 in this case are given by

$$S_1 = \frac{1}{\sqrt{|\alpha|^2 + |\beta^2|}}(\bar{\alpha} - \epsilon\beta, \bar{\beta} + \epsilon\alpha),$$

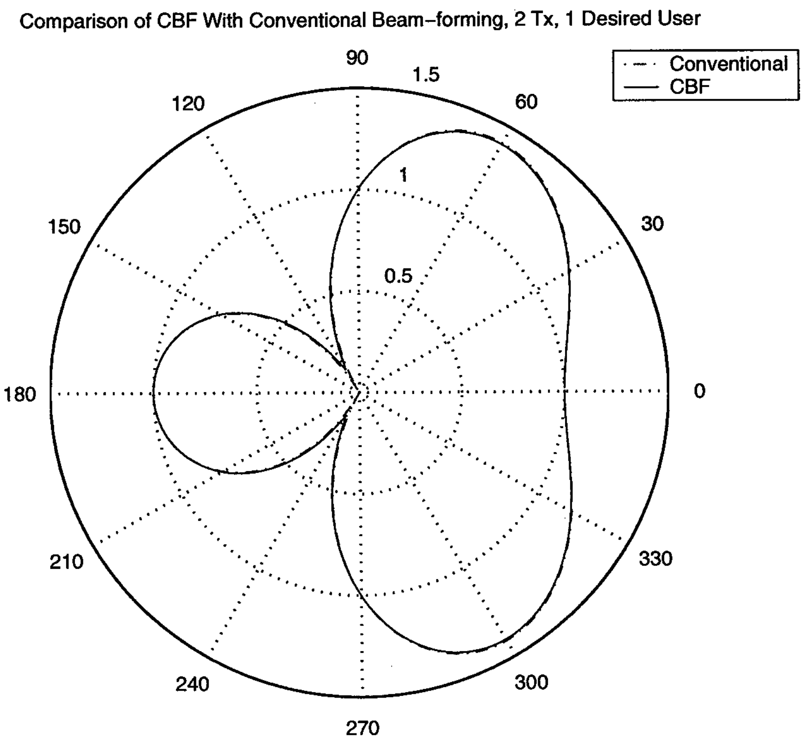
$$S_2 = \frac{1}{\sqrt{|\alpha|^2 + |\beta^2|}}(\bar{\alpha} + \epsilon\beta, \bar{\beta} - \epsilon\alpha),$$

with $S_{2l-1} = S_1$ and $S_{2l} = S_2$ for $l = 1, 2, \cdots, \lfloor \frac{L}{2} \rfloor$, with $S_L = \frac{1}{\sqrt{|\alpha|^2+|\beta^2|}}(\bar{\alpha}, \bar{\beta})$ when L is odd.

Time Domain CBF



Time Domain CBF



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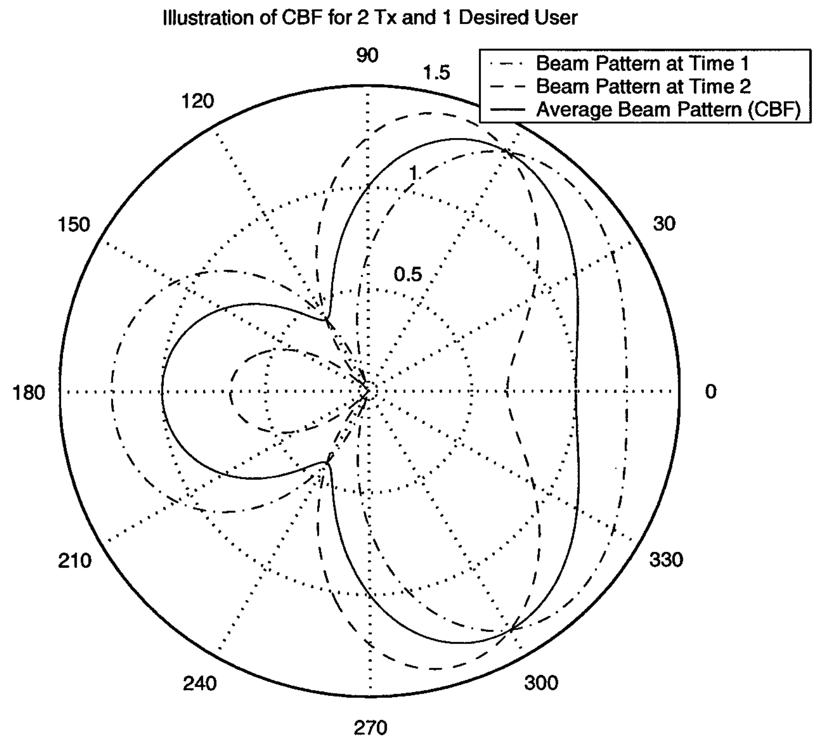
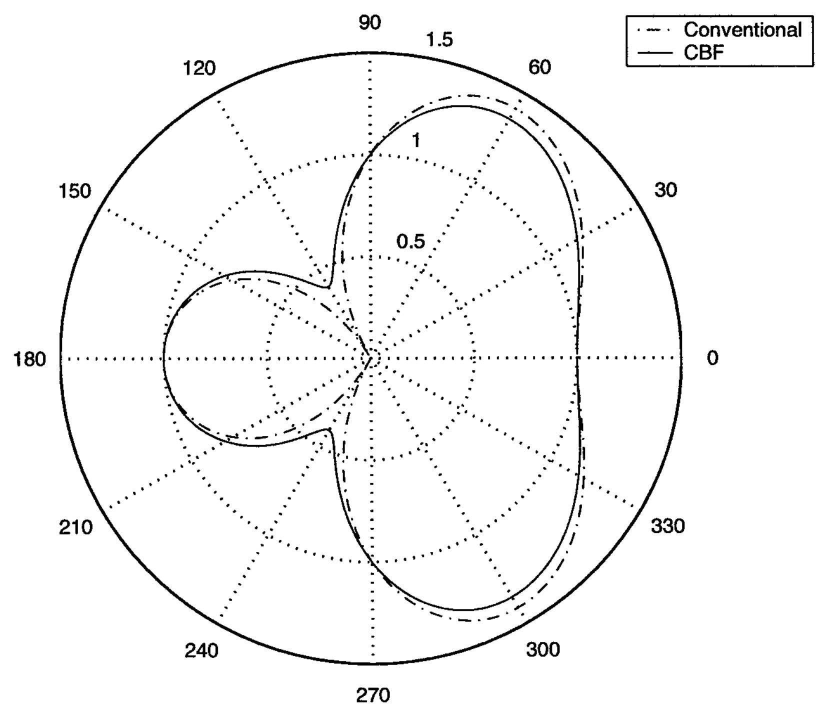


Time Domain CBF

Comparison of CBF With Conventional Beam–forming, 2 Tx, 1 Desired User



Other Issues

- Analysis show that the complexity of complementary beam-forming is approximately twice as much as that of the conventional beam-forming.
- It has been observed via simulations that using complementary beam-forming significantly enhance the performance of a heavily loaded smart antenna enhanced IEEE 802.11 system as compared to the case when conventional beam-forming is employed.

Conclusions

- Smart antennas are an appealing solution for increasing the range and throughput of IEEE 802.11 systems because they are backward compatible.
- Combining smart antennas and CSMA produce a host of new challenges.
- An example of these problems is the hidden beam problem.
- We proposed complementary beam-forming to address this problem.